High brightness drive beam generation and kinetic plasma instabilities relevant to acceleration in dense plasmas

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U.S. DEPARTMENT OF ENERGY

Workshop on Beam Acceleration in Crystals and Nano-structures, Fermilab

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Introduction

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- **Drivers needed for exciting wakes in dense plasmas (crystals & nano-structures)**

- **X-ray**
  - optical laser (surface compression)
  - e- beam (FEL)
- **10 keV?**

- **Electron beam**
  - optical laser (LWFA)
  - e- beam (PWFA)
- **10s MeV-GeV**
- **high brightness**

- **This talk will cover two topics:**
  - **generation of high brightness e- beams in a PWFA using downramp trapping**
  - **kinetic plasma instabilities relevant to beam-plasma interaction**

Outline

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- High brightness beam generation using downramp trapping
  - concept
  - simulation results
- Kinetic instabilities relevant to acceleration in dense plasmas
  - kinetic instabilities in beam-plasma system
  - experimental investigation using optical-field ionized plasmas
  - <u>current filamentation experiment at FACET-II</u>

Downramp trapping is capable to generate high brightness beams

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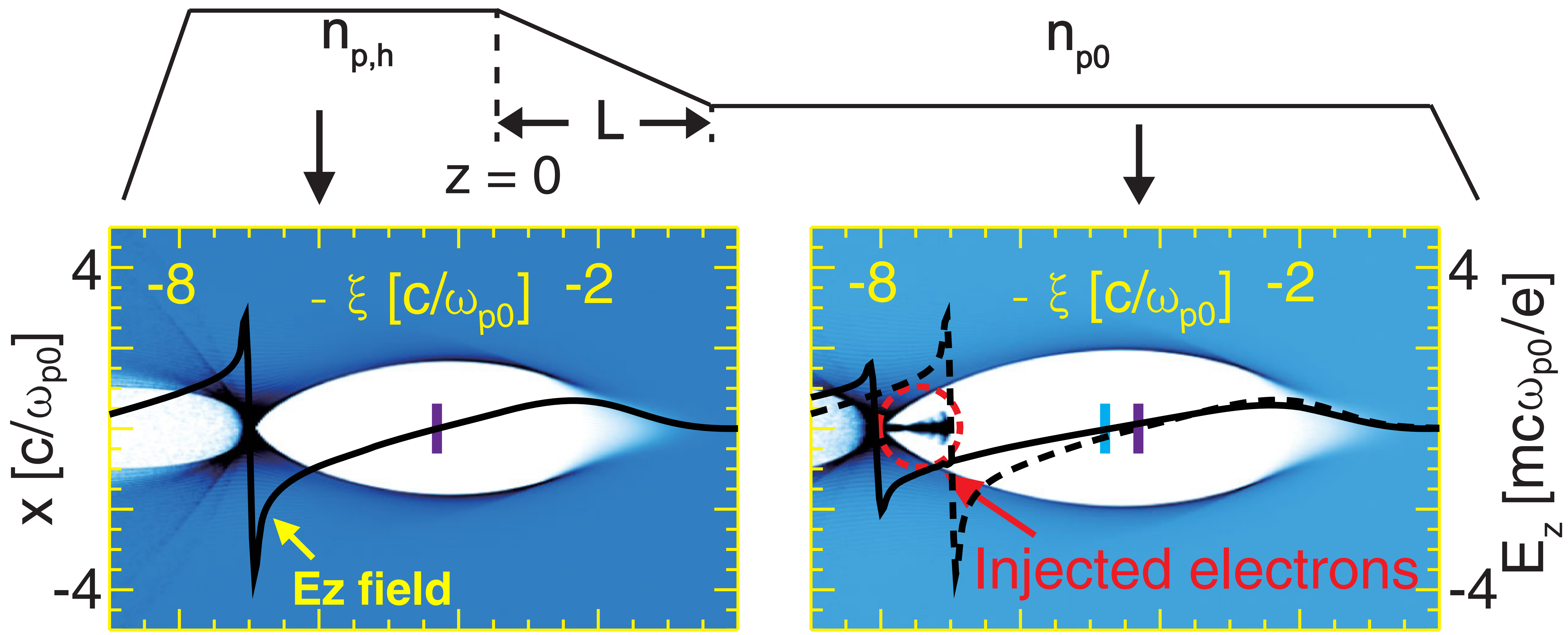
- Conceptual illustration of downramp trapping:



Xinlu Xu et al., Phys. Rev. Accel. Beams (2017)

The concept of downramp trapping was firstly proposed by S. Bulanov (1998) and H. Suk (2003) using 1D analysis.

S. Bulanov, et al., Phys. Rev. E 58, R5257 (1998);
H. Suk, et al., Phys. Rev. Lett. 86, 1011 (2001)

Mechanism of reducing emittance of the injected beam

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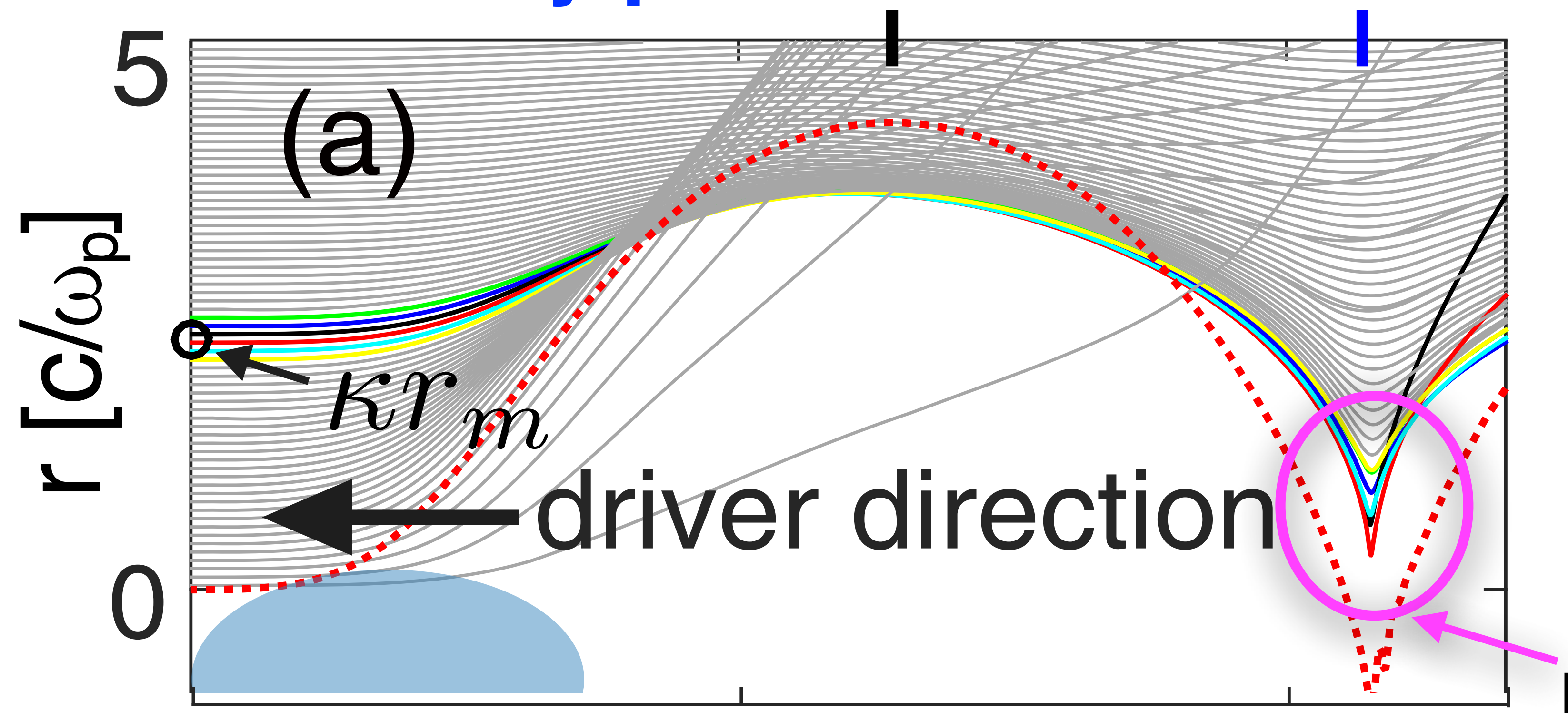
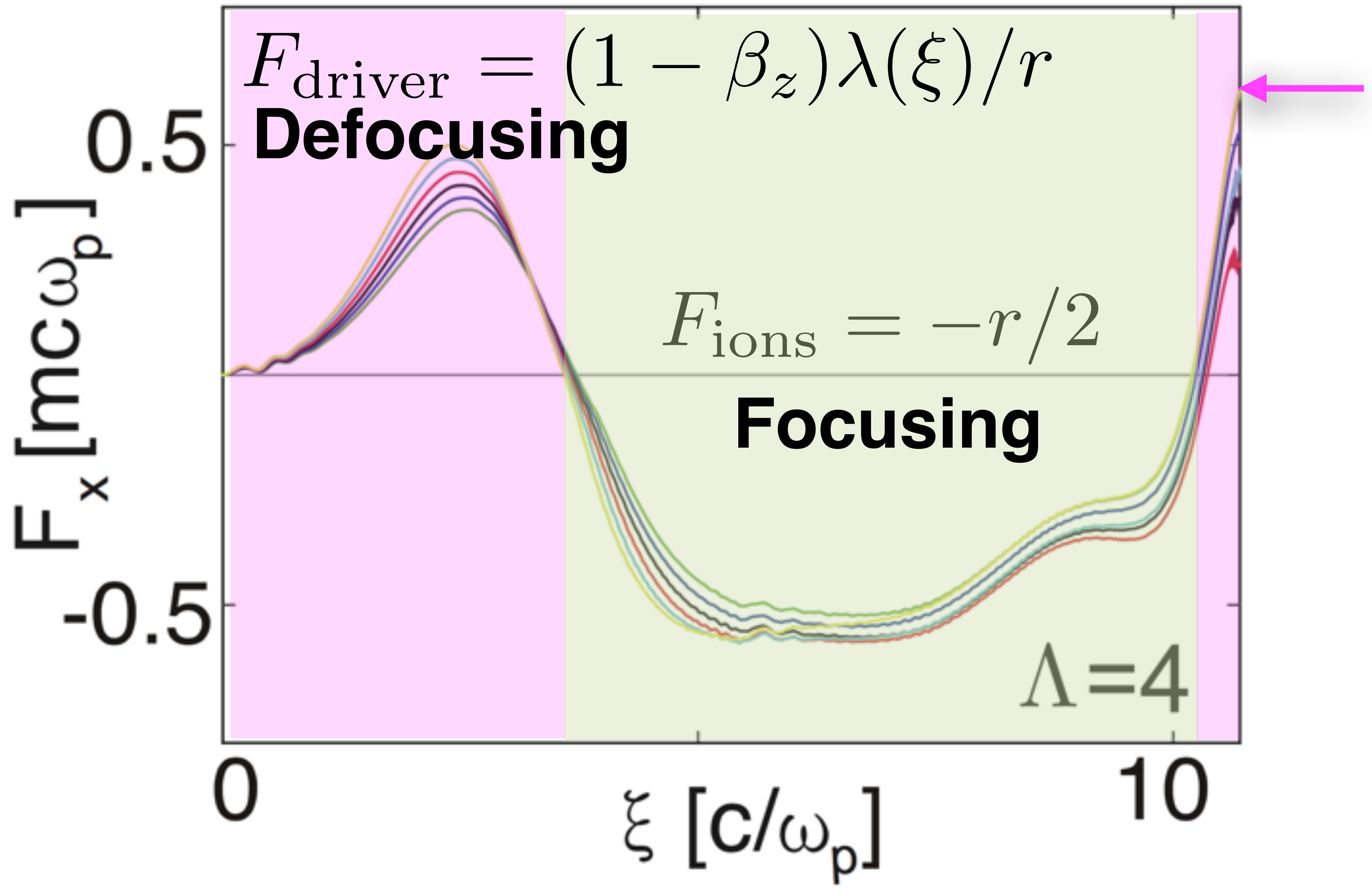
Trajectories of electrons forming a wake in an uniform density plasma:





$F_{\mathrm{e}} = -(r/2)(1-\beta_z)\mathrm{d}^2\psi_0^2/\mathrm{d}\xi^2$

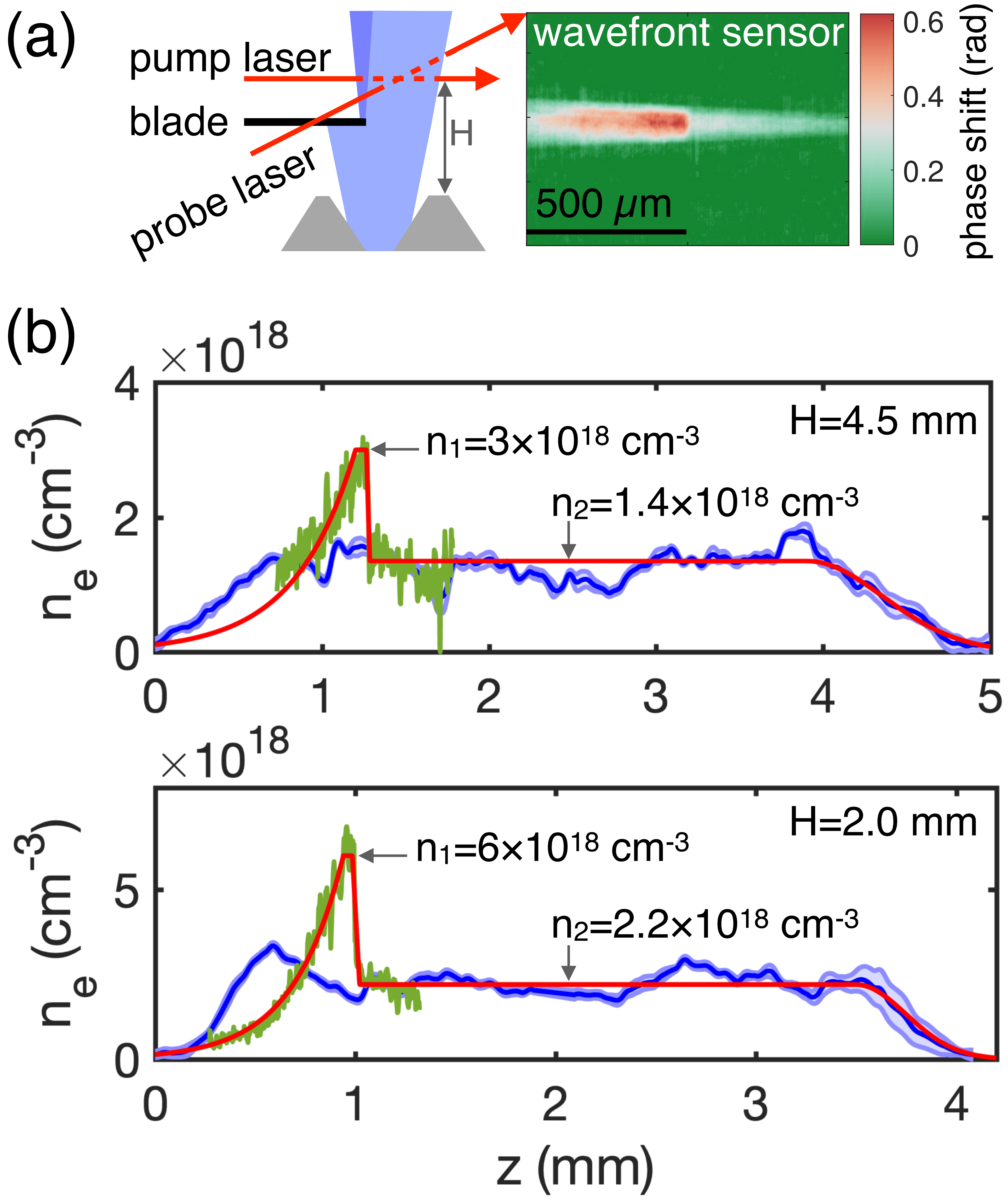
Defocusing

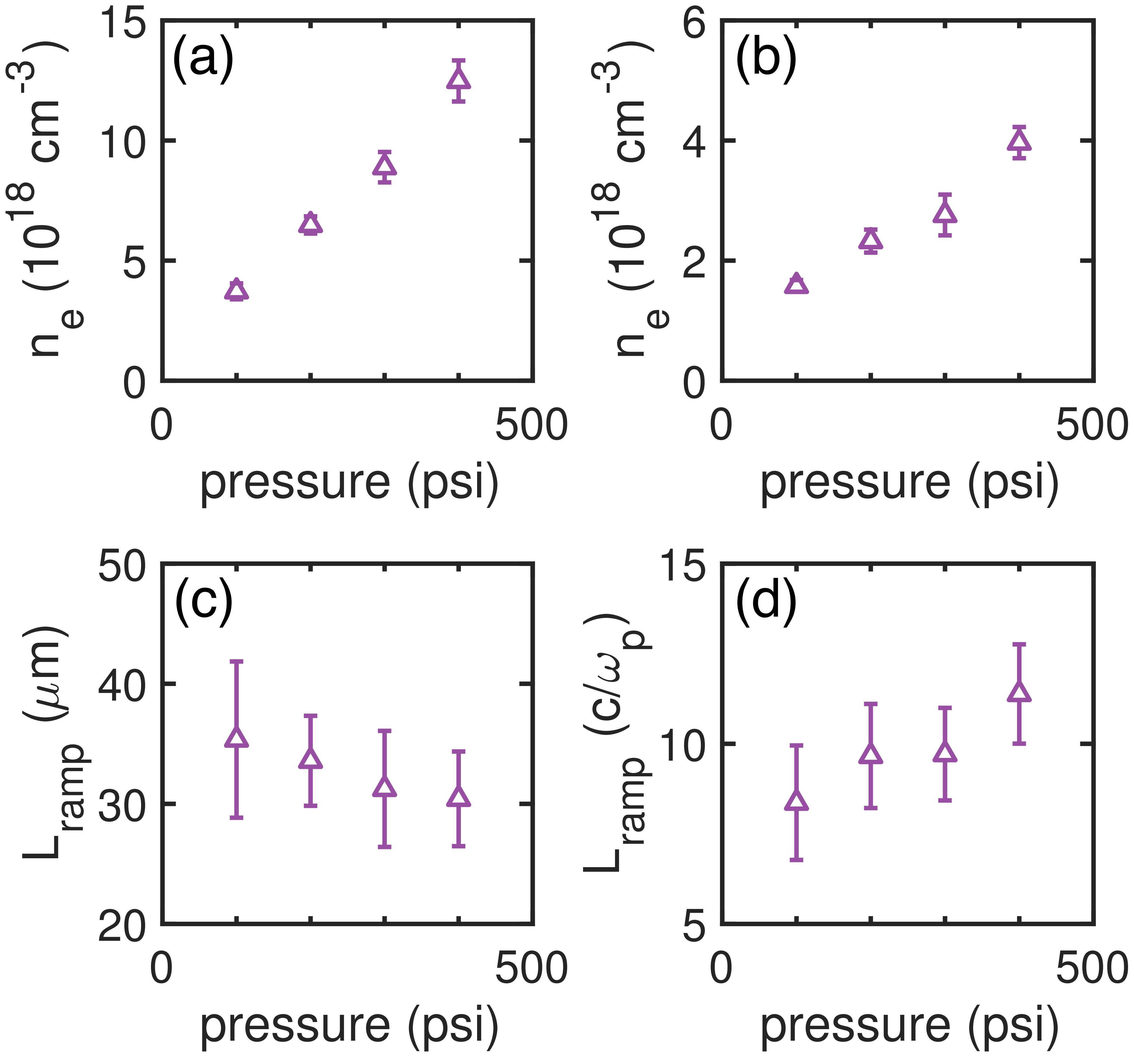
$|\frac{\mathrm{d}\psi_0^2}{\mathrm{d}\xi^2}| \gg 1$

- **as the electrons being pulled back to the axis, their radial velocity initially increases, but is reduced as these electrons approach the axis** (actually most sheath electrons are reflected to form a second bubble)

- **beam current Λ>1**
- **ramp length >>c/ωp**

Plasma source developed at UCLA





ramp length ~10 c/ωp, adiabatic injection

3D simulation results: beam parameters

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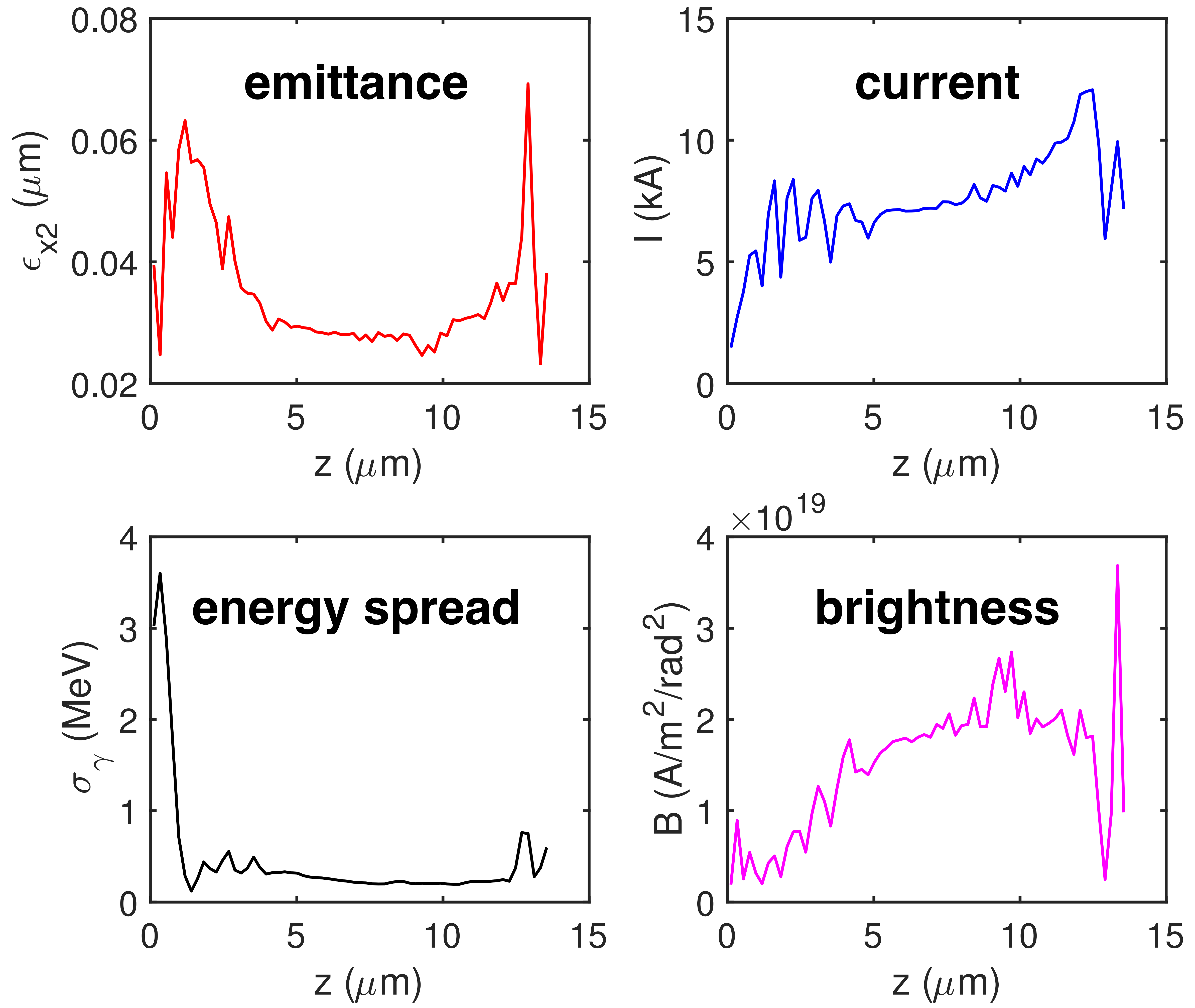
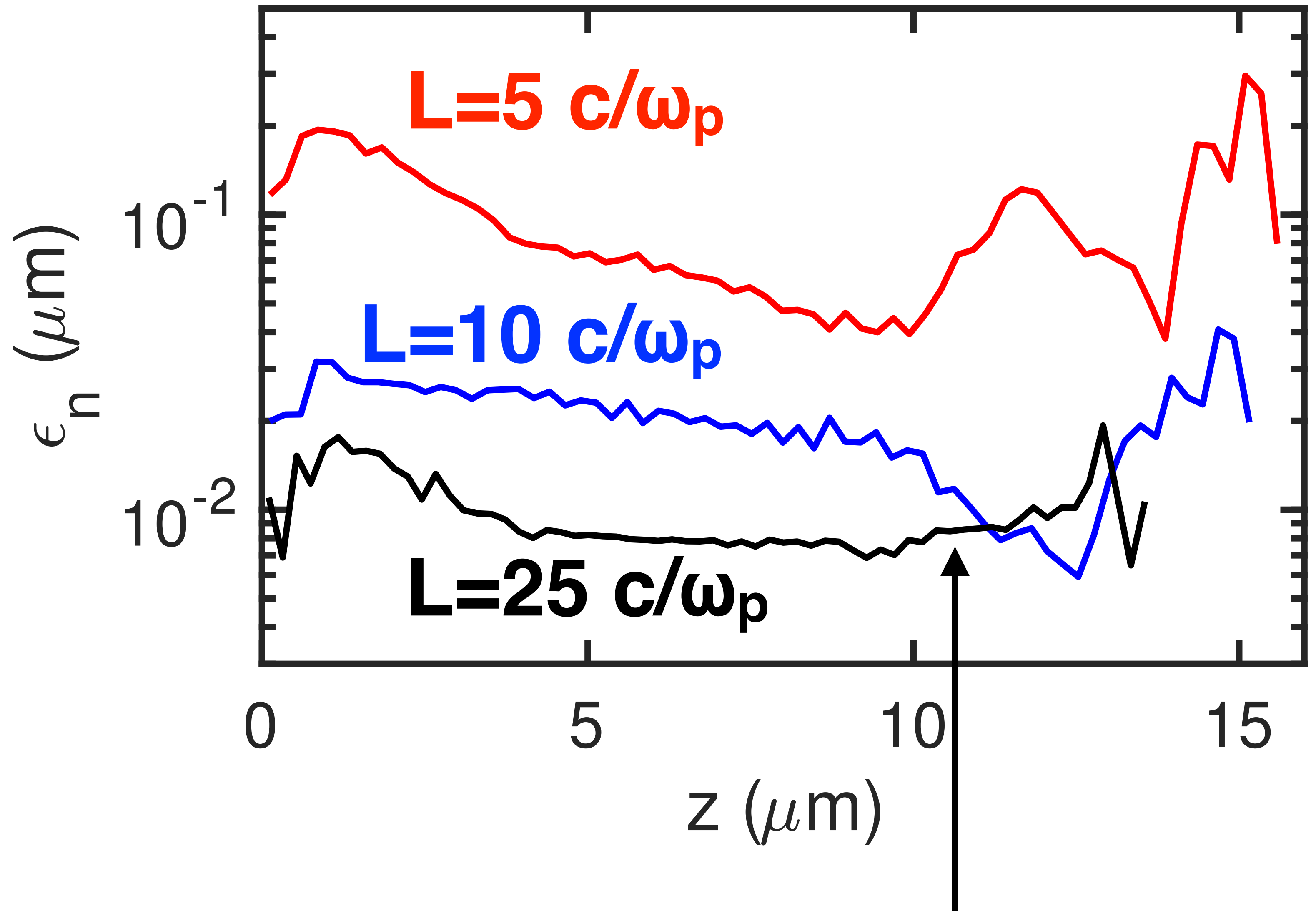
A simulation example to show the parameters of the injected bunch:

downramp: 6e18 cm^{-3} to 2.2e18 cm^{-3} in L=25 c/ω_p



ε_n as a function of ramp length:



10 nm which is about 2 orders of magnitude lower than the current available values in plasma-based accelerators.

The emittance is sensitive to the symmetry of the wake (driver)

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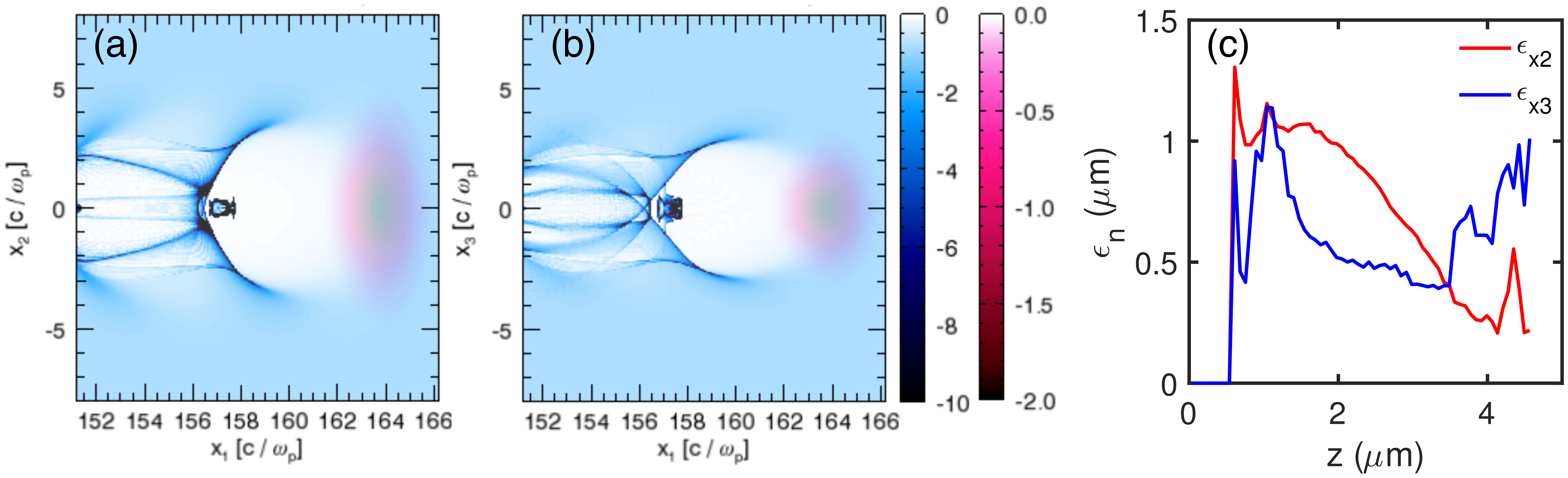
downramp: 3e18 cm^{-3} to 2.2e18 cm^{-3} in L=10 c/ω_p

σx2=6.6 μm, σx3=4.5 μm

the slice emittance increases by a factor of ~10 compared to the symmetric driver case



The current profile of the bunch depends on ramp shape

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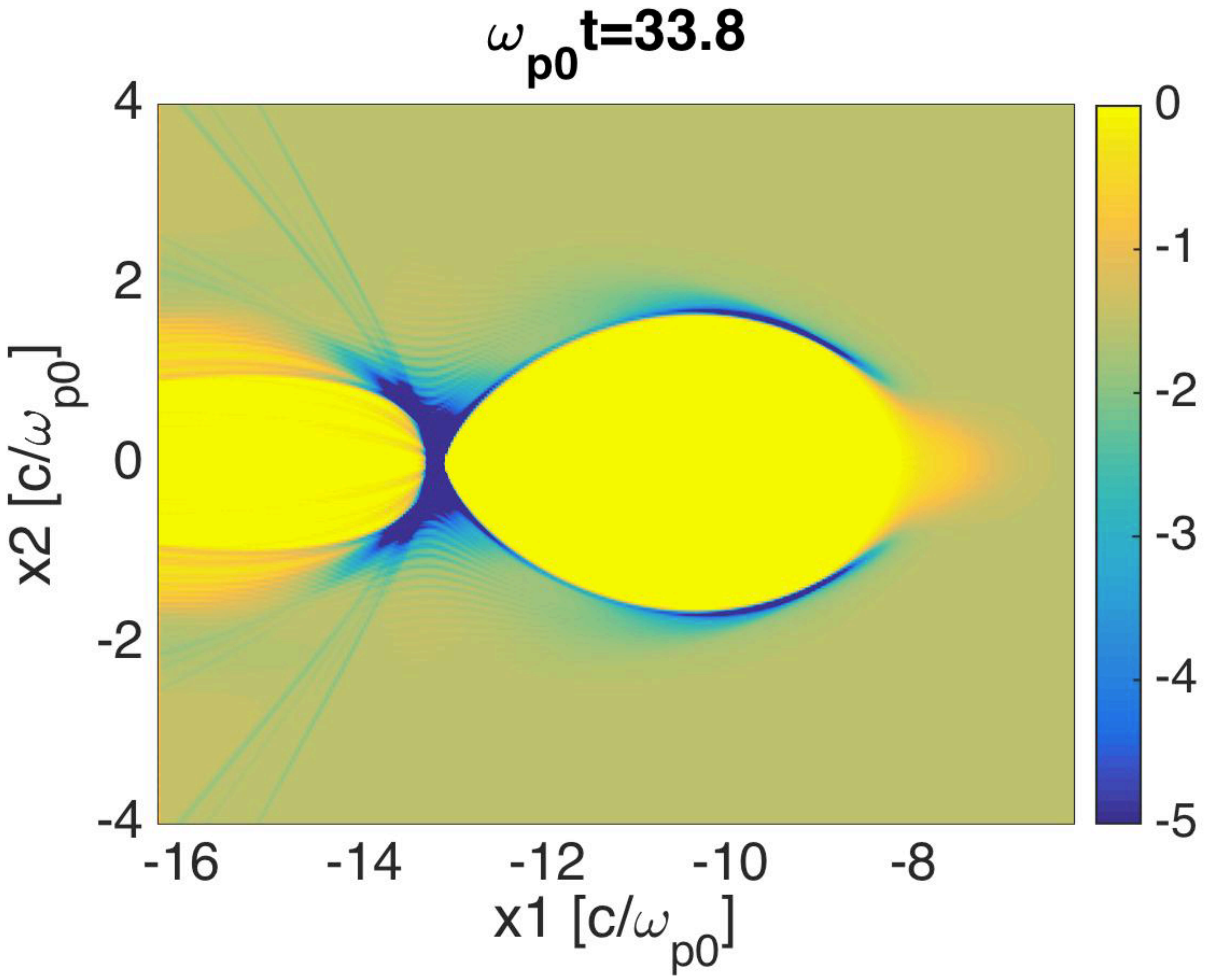
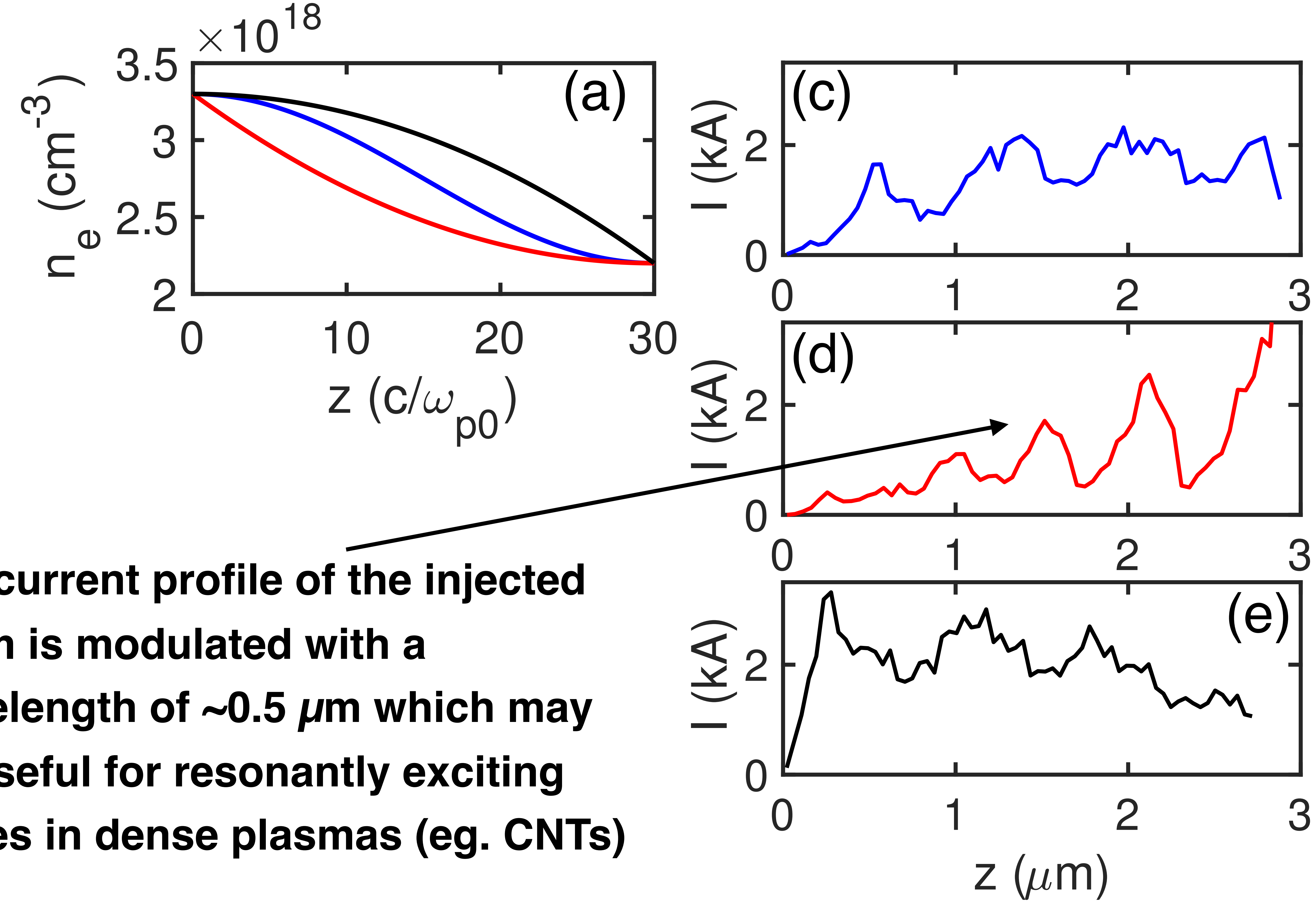
there is a one-to-one mapping between the initial (z_i) and the final (ξ_f) coordinates of the injected electrons, which will

- <u>introduce an initial energy chirp</u>
- <u>affect the current profile</u>



current profile depends on ramp shape



The current profile of the injected beam is modulated with a wavelength of ~0.5 μm which may be useful for resonantly exciting wakes in dense plasmas (eg. CNTs)

Courtesy of Dr. Xinlu Xu

The emittance and brightness of the injected beam scale with plasma density

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	I	ε_n, τ, σ_r	B	σ_E/E	n	Q
E beams	n_{p0}^{0}	$n_{p0}^{-0.5}$	n_{p0}^{1}	n_{p0}^{0}	n_{p0}^{1}	$n_{p0}^{-0.5}$
	Ramp length			Optimal acceleration length		
Plasma	$\propto n_{p0}^{-0.5}$			$\propto n_{p0}^{-0.5}$		

Case study: 1.5 $n_{p0} \rightarrow n_{p0}$, ramp length L=250 c/ω_{p0}:

	n_{p0} [cm^{-3}]	I [kA]	ε_n [nm]	τ [fs]	σ_r [μm]	B [$A/m^2/rad^2$]	E [MeV]	σ_E/E	Q [pC]
Injected beam	10^{18}	14	80	10	0.2	4×10^{18}	620	1.5×10^{-3}	140
	10^{20}	14	8	1	0.02	4×10^{20}	620	1.5×10^{-3}	14

	n_{p0} [cm-3]	Density change [cm^{-3}]	L_{ramp} [mm]	L_{acc} [mm]
Plasma	10^{18}	5×10^{17}	1.33	3.3
	10^{20}	5×10^{19}	0.133	0.33

Courtesy of Dr. Xinlu Xu

Outline

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- High brightness beam generation using downramp trapping
  - concept
  - simulation results
  - downramp trapping experiment at FACET-II
- **Kinetic instabilities relevant to acceleration in dense plasmas**
  - **kinetic instabilities in beam-plasma system**
  - **experimental investigation using optical-field ionized plasmas**
  - **current filamentation experiment at FACET-II**

Kinetic instabilities in beam-plasma systems

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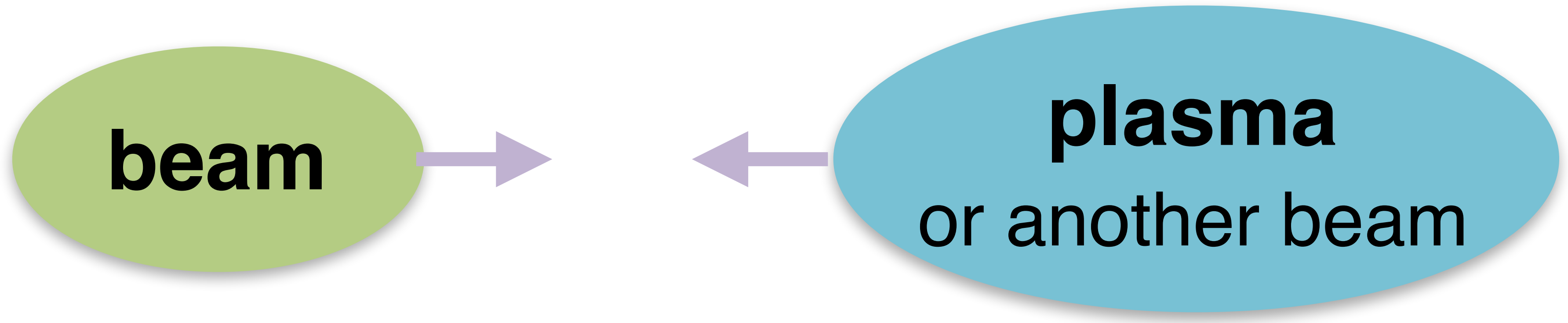
A beam-plasma system may be unstable to two-stream and current filamentation instability.



two-stream instability

↓

drives longitudinal plasma waves
(Langmuir waves)

↓

- "thermalize" the plasma

filamentation/Weibel instability

↓

self-generates and
amplifies magnetic fields

↓

- isotropize the plasma

Kinetic plasma instabilities play important roles in both laboratory and astrophysical plasmas

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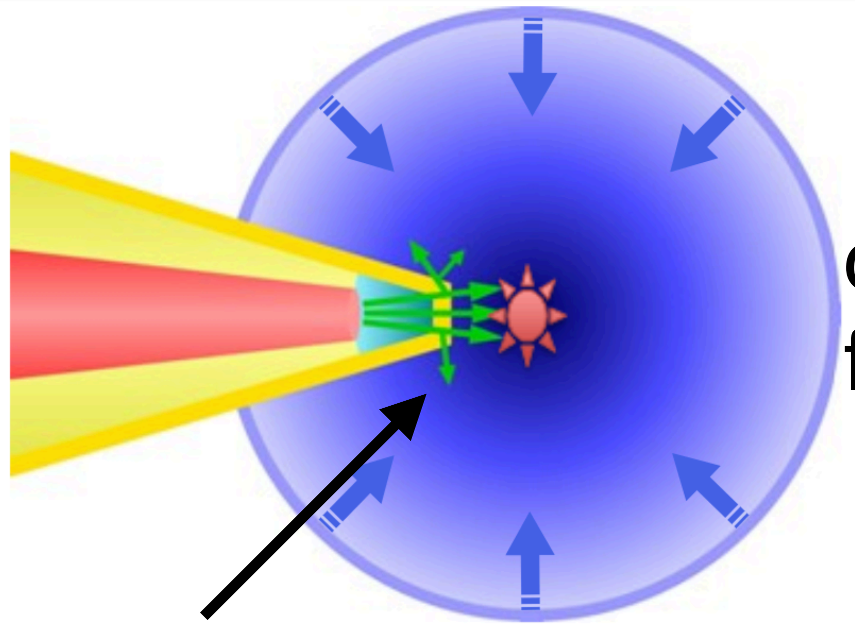
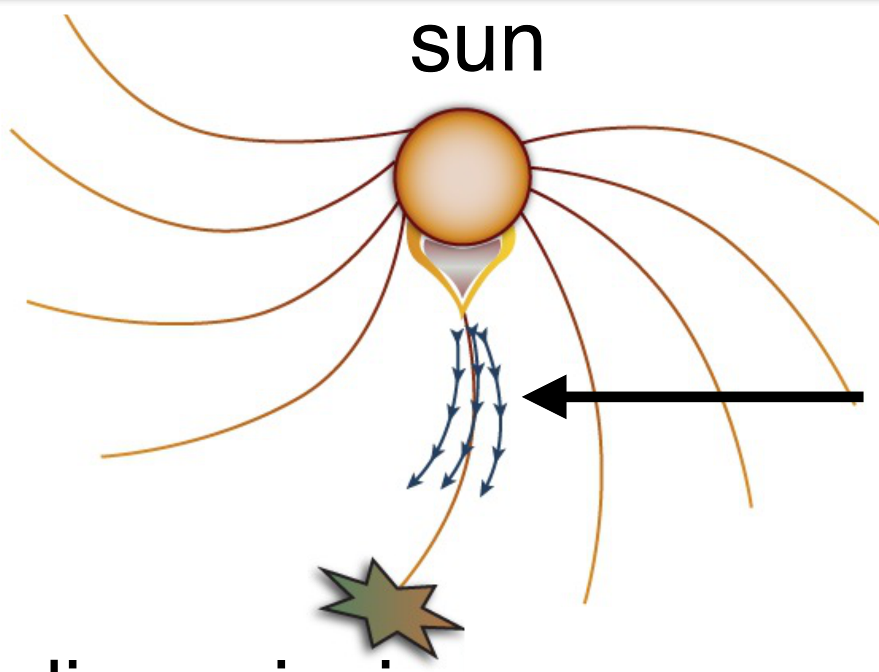
Fast ignition



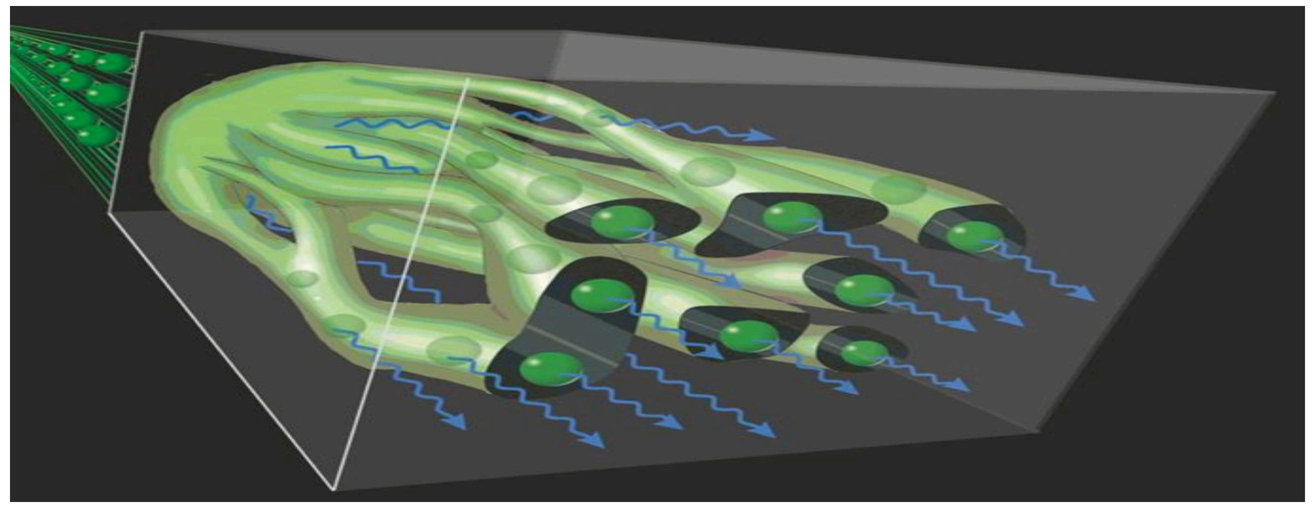
Solar radio burst



Collisionless shock

colliding plasma creates collisionless shocks

Gamma ray flash



filamentation of e- beam in dense plasma generates bright γ-ray flashes

Experimental study of kinetic plasma instabilities at UCLA

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- **One way to study electron current filamentation instability is to send an electron beam through a plasma and to observe the filaments of the e- beam once it breaks up.**

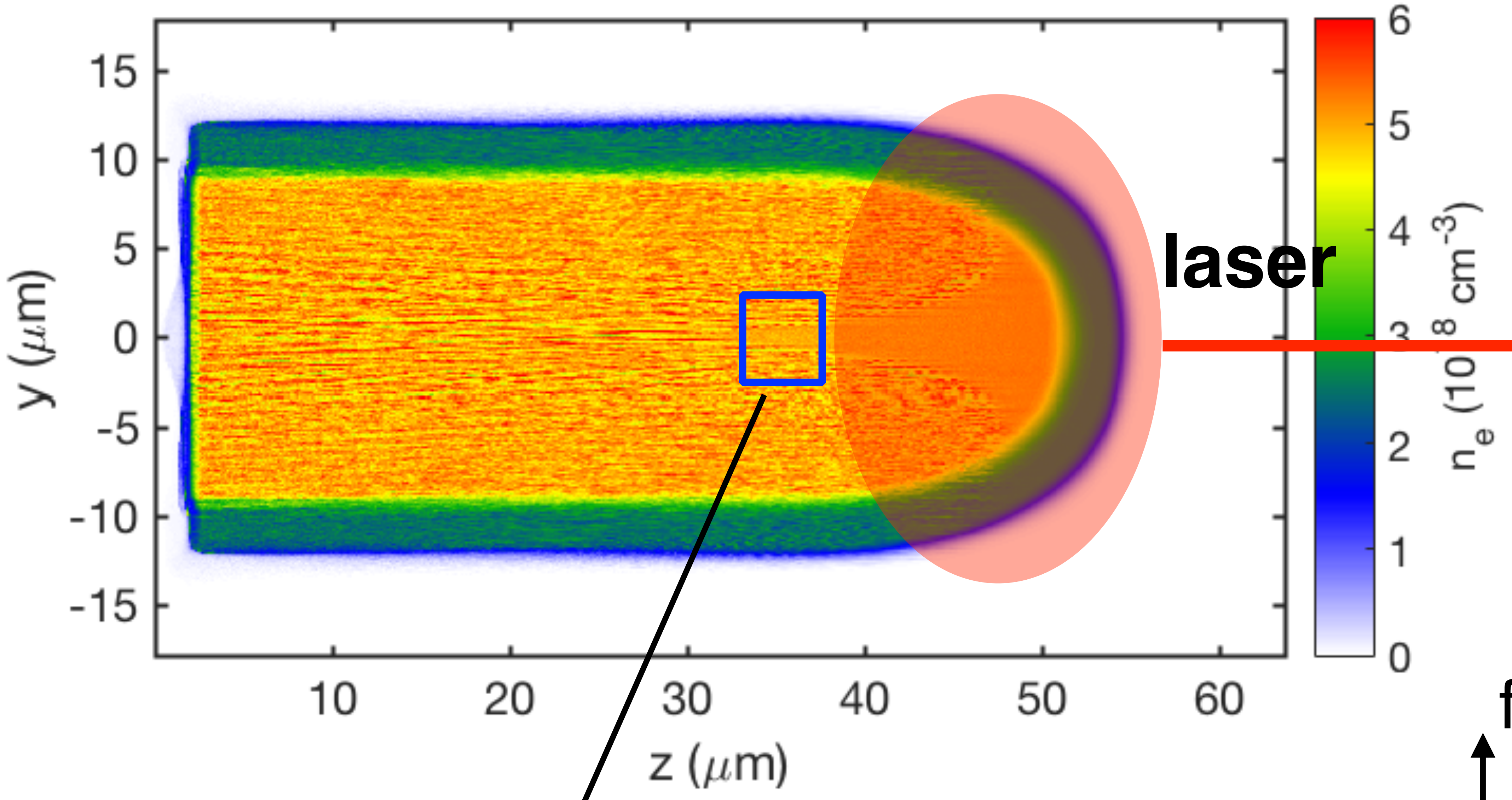
B. Allen et al., Phys. Rev. Lett. (2012)

- **Recently, we have developed a new laboratory platform for (quantitatively) studying kinetic plasma instabilities.**

- **We use optical-field-ionization (OFI) to initialize plasmas with anisotropic (non-Maxwellian) velocity distributions to trigger kinetic plasma instabilities.**
  - streaming instability
  - filamentation instability
  - Weibel instability

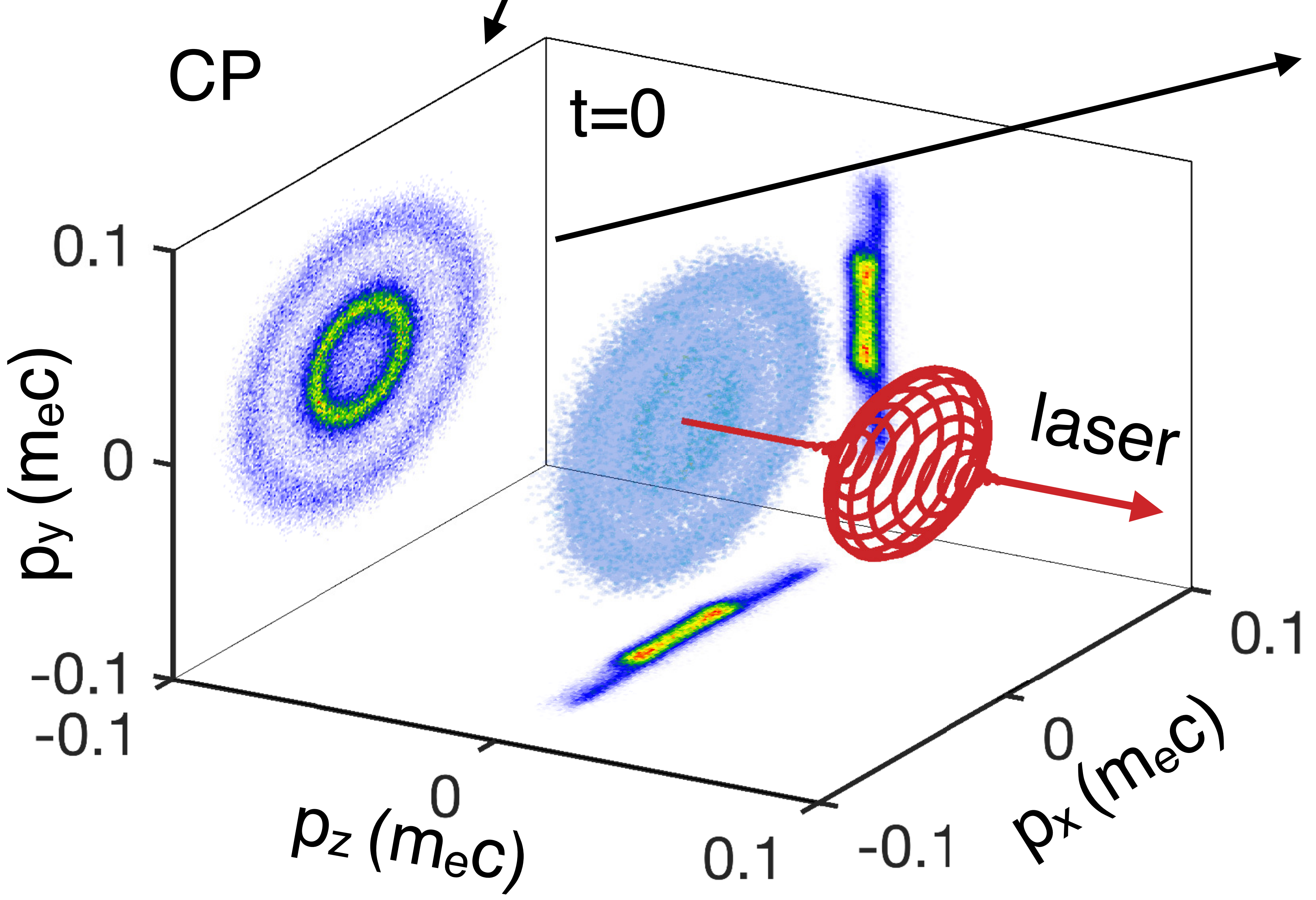
- **We use time-resolve Thomson scattering to probe the plasma density fluctuations associated with these instabilities to get their frequency and the growth rate.**

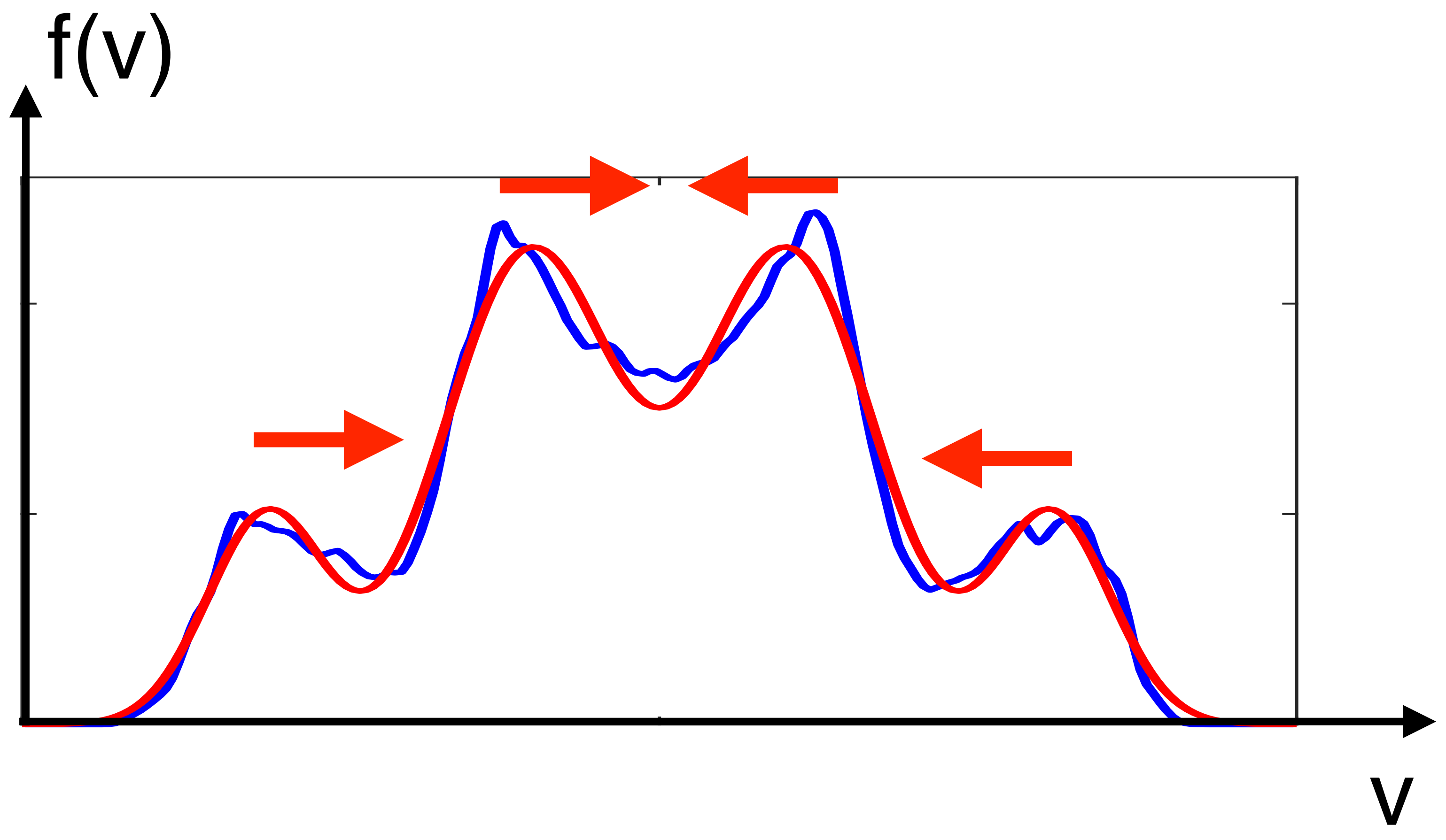
Anisotropic EVD initialized by a circularly polarized laser



laser:
circular polarization
τ=50 fs, w_0=8 μm
I=1.6×10^{17} W/cm^2
a0~0.2

Helium is fully ionized
in ~10 fs, n_e=5×18 cm^{-3}

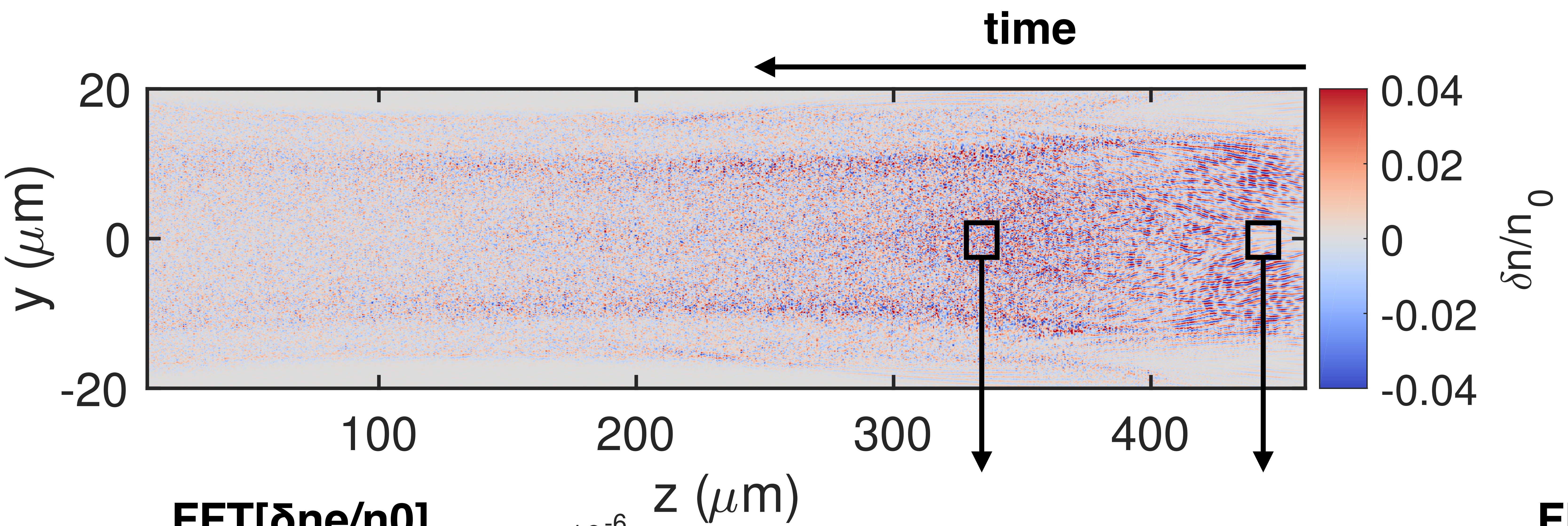


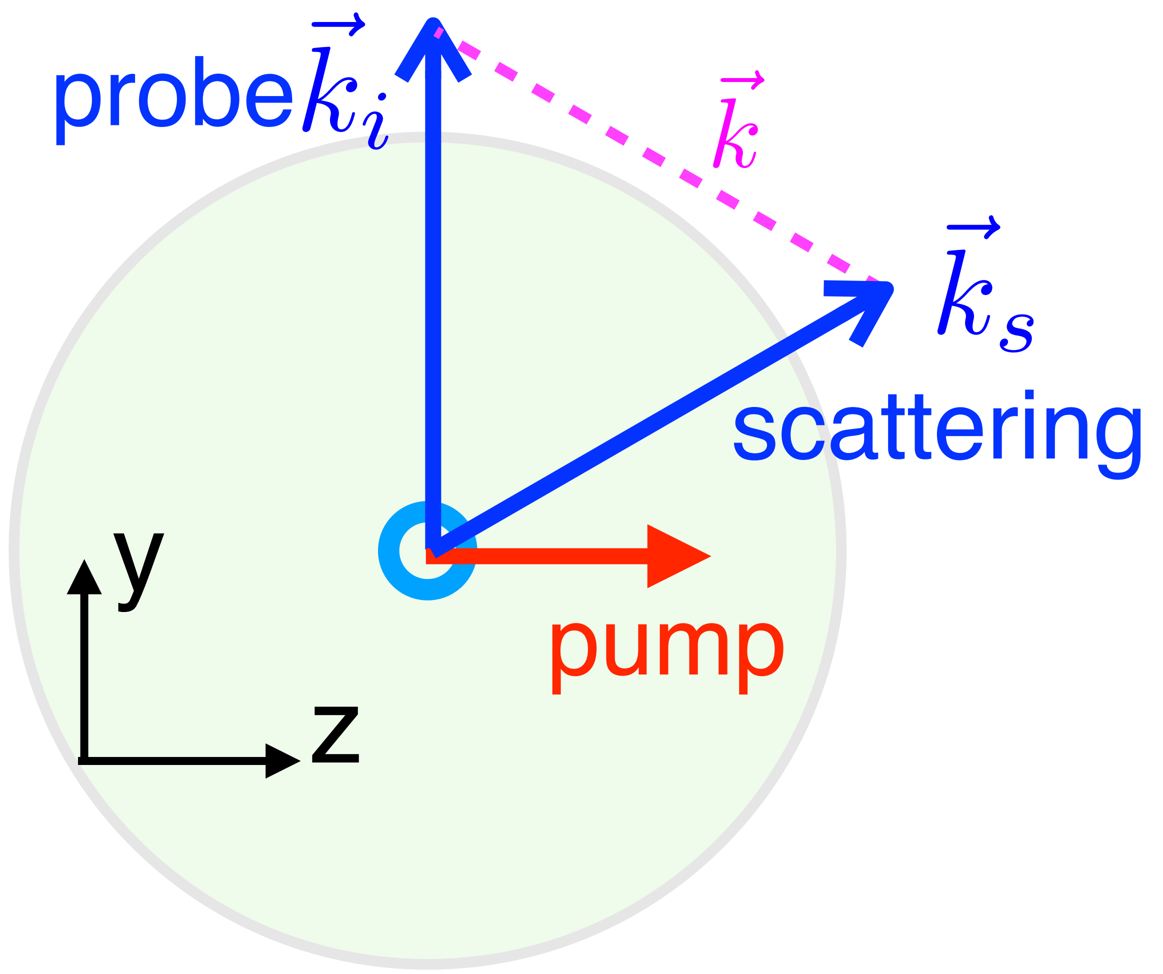


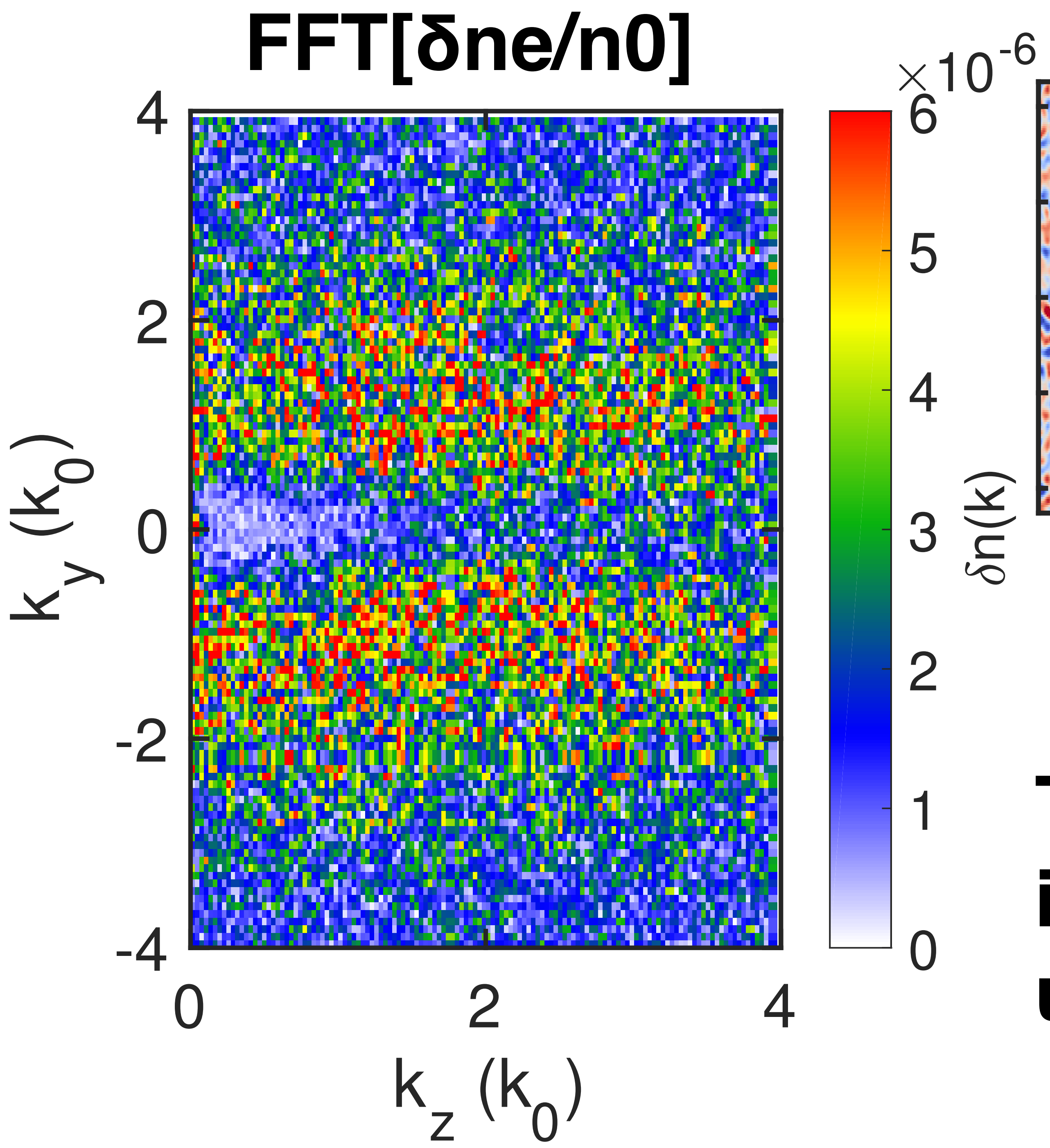
the initial EVD can be well approximated by four drifting Maxwellians (interpenetrating streams)

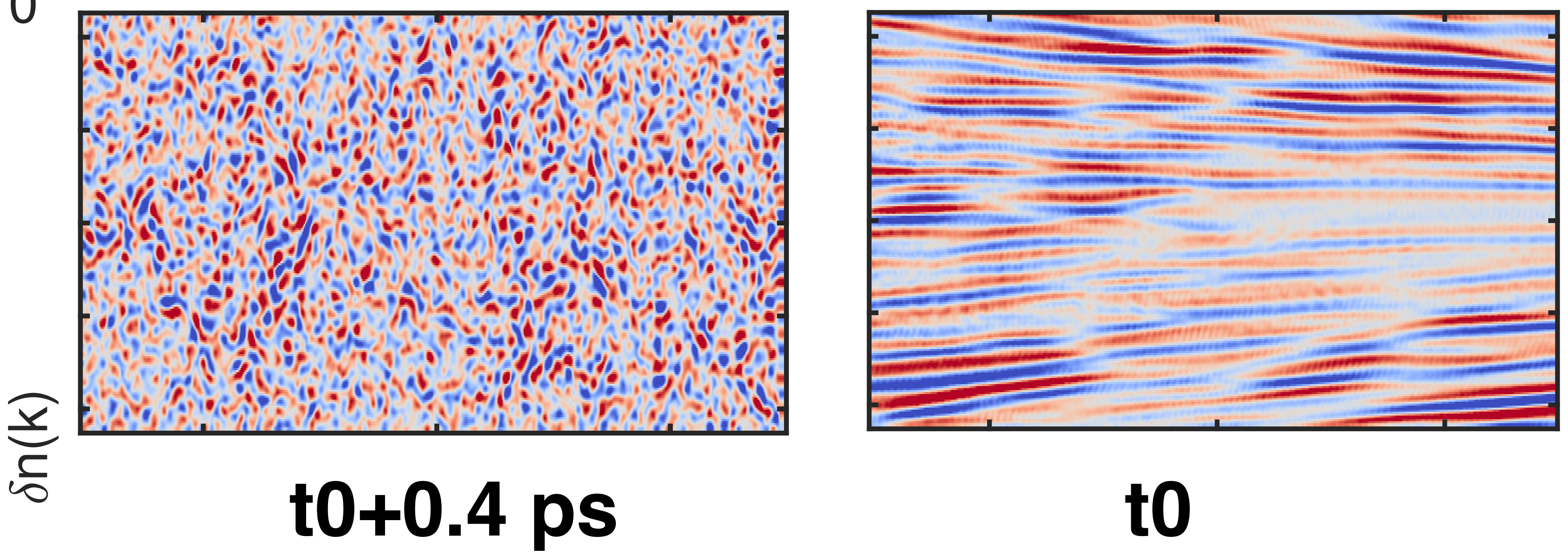
unstable to streaming and filamentation instabilities;

Signature of instabilities: density fluctuations

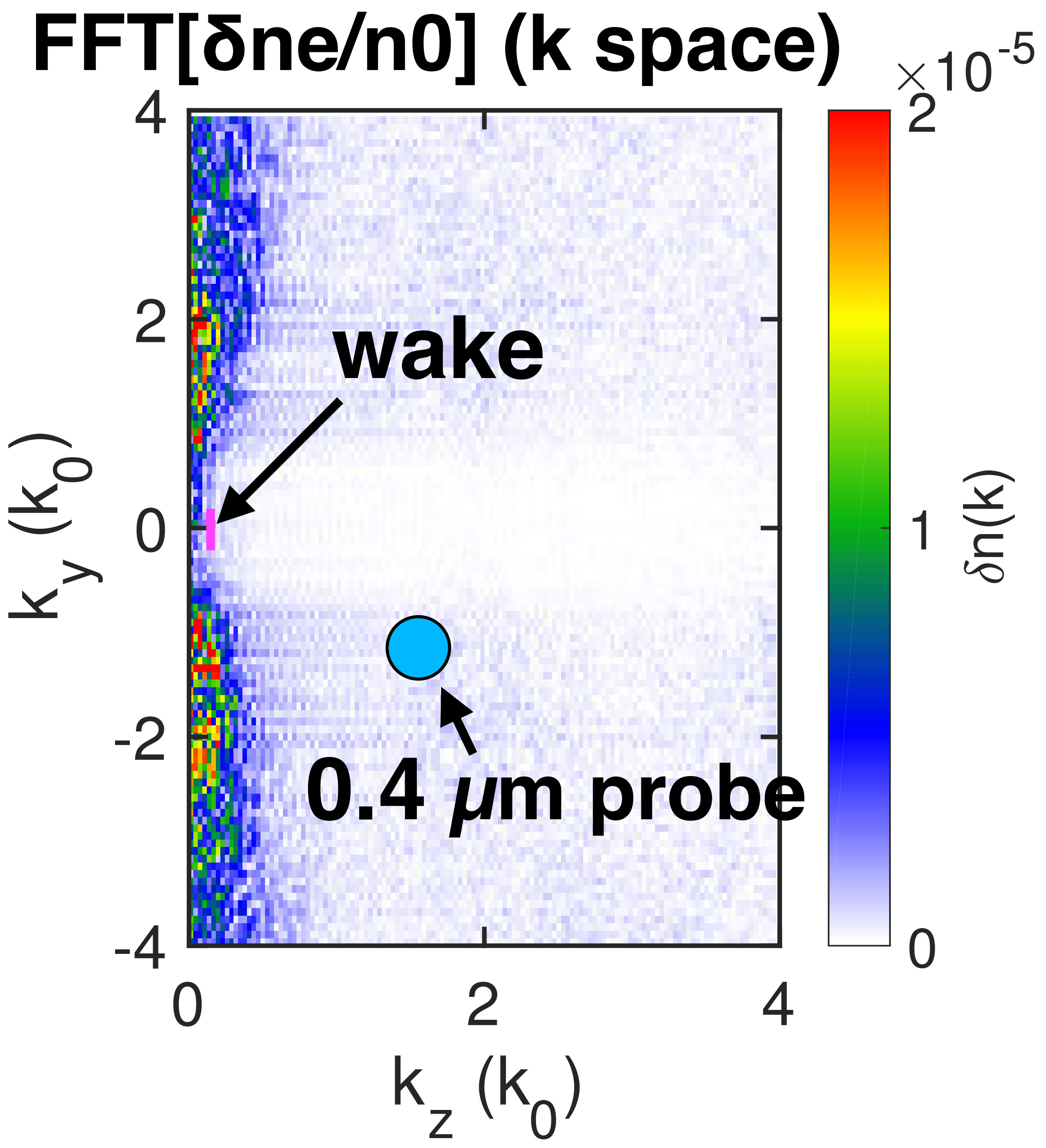








The magnitude of density fluctuation is few percent, but is measurable using Thomson scattering



Measured Thomson scattering spectra

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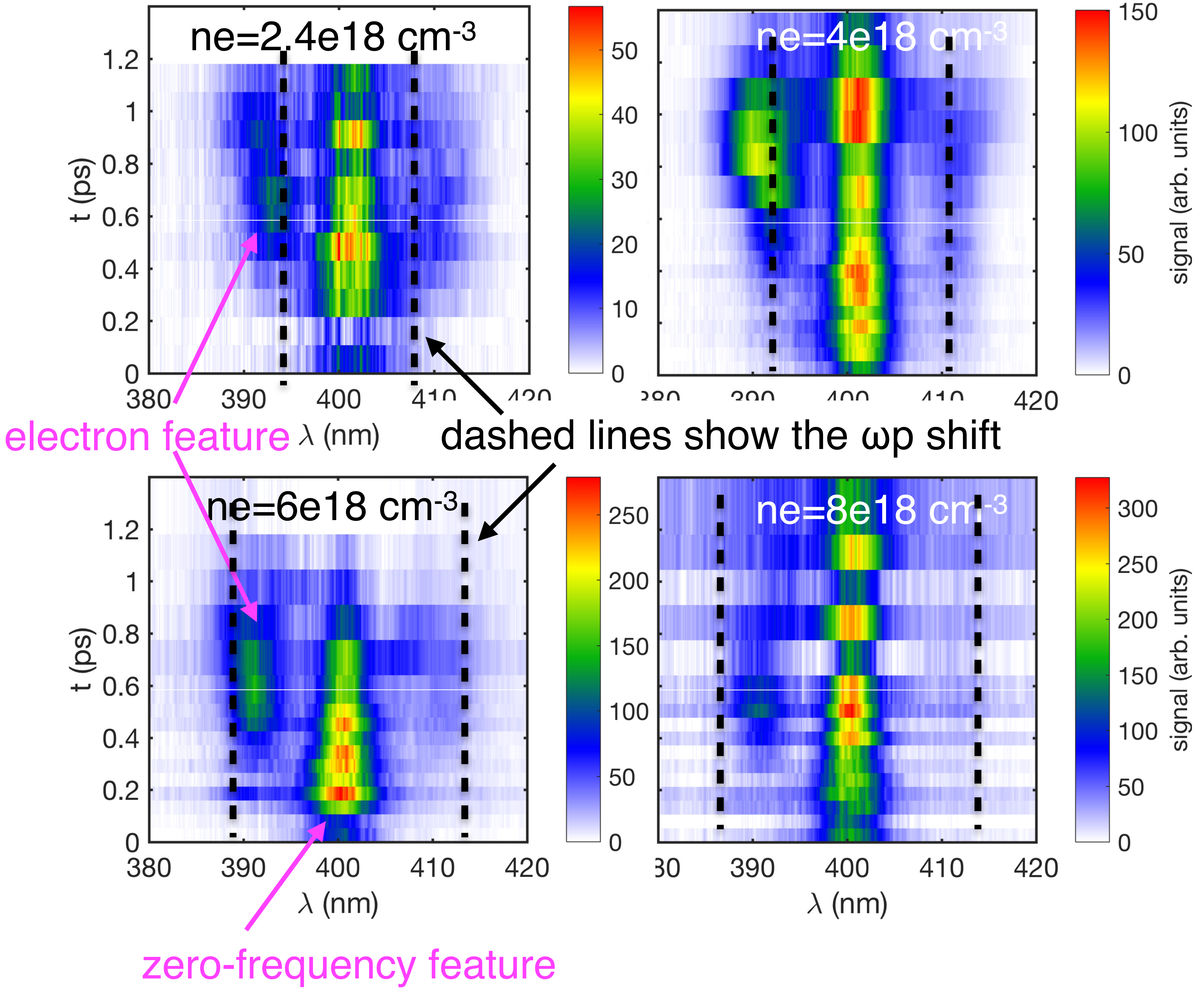

- Laser parameters:
  - pump: 0.8μm, 10mJ, 45fs
  - probe: 0.4μm, 45fs
  - t0 accuracy: ~100 fs;
  - temporal resolution: ~45 fs

Electron feature:

1. **shot-lived (compared to collision/recombination time)**
2. **constant spectral shift**

streaming instability

Zero-frequency feature:

We call it zero-frequency feature instead of "ion feature" because the unshifted signal at 0.4 μm also corresponds to instabilities.

filamentation/Weibel instability

Evolution of the streaming instability

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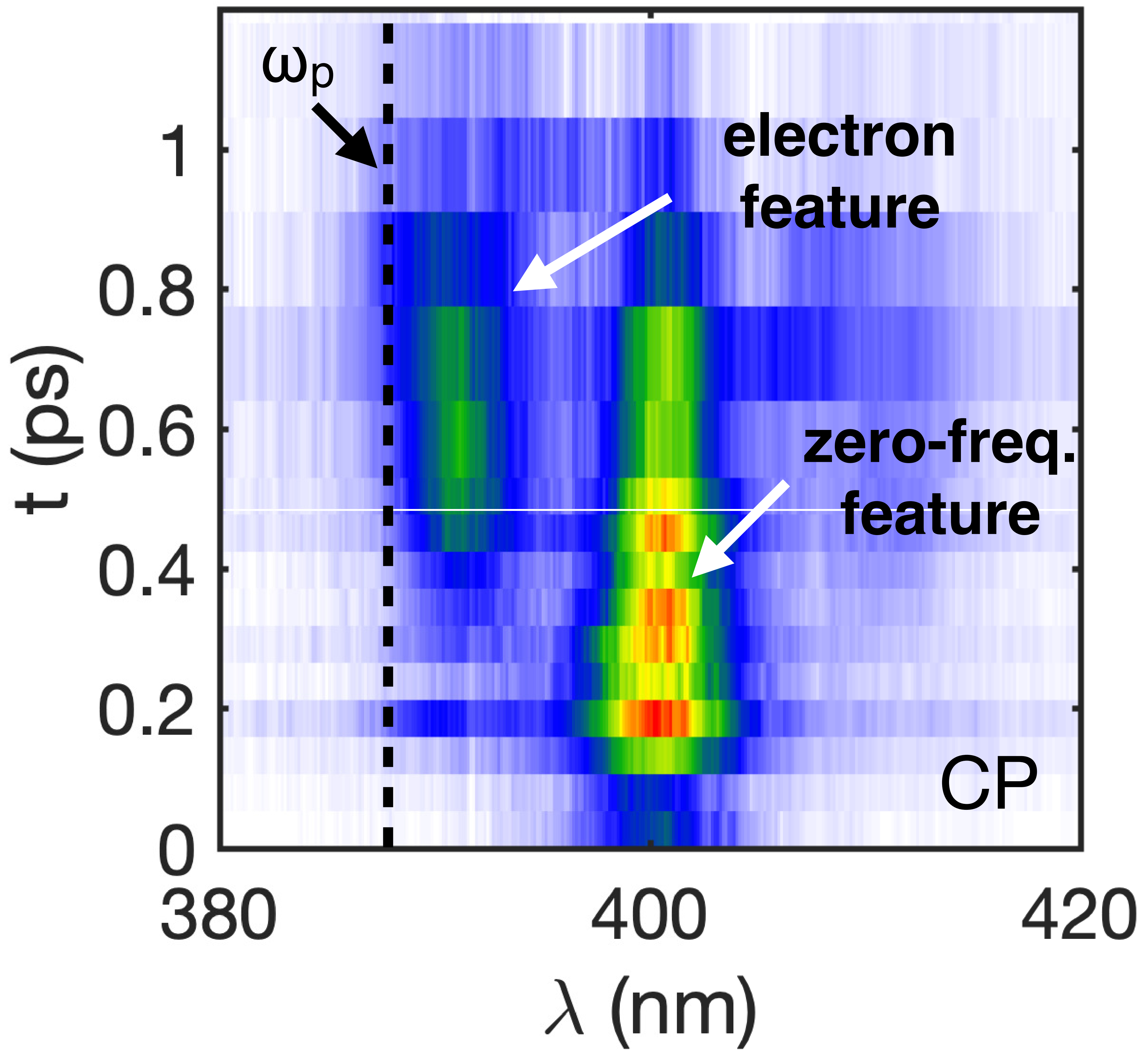
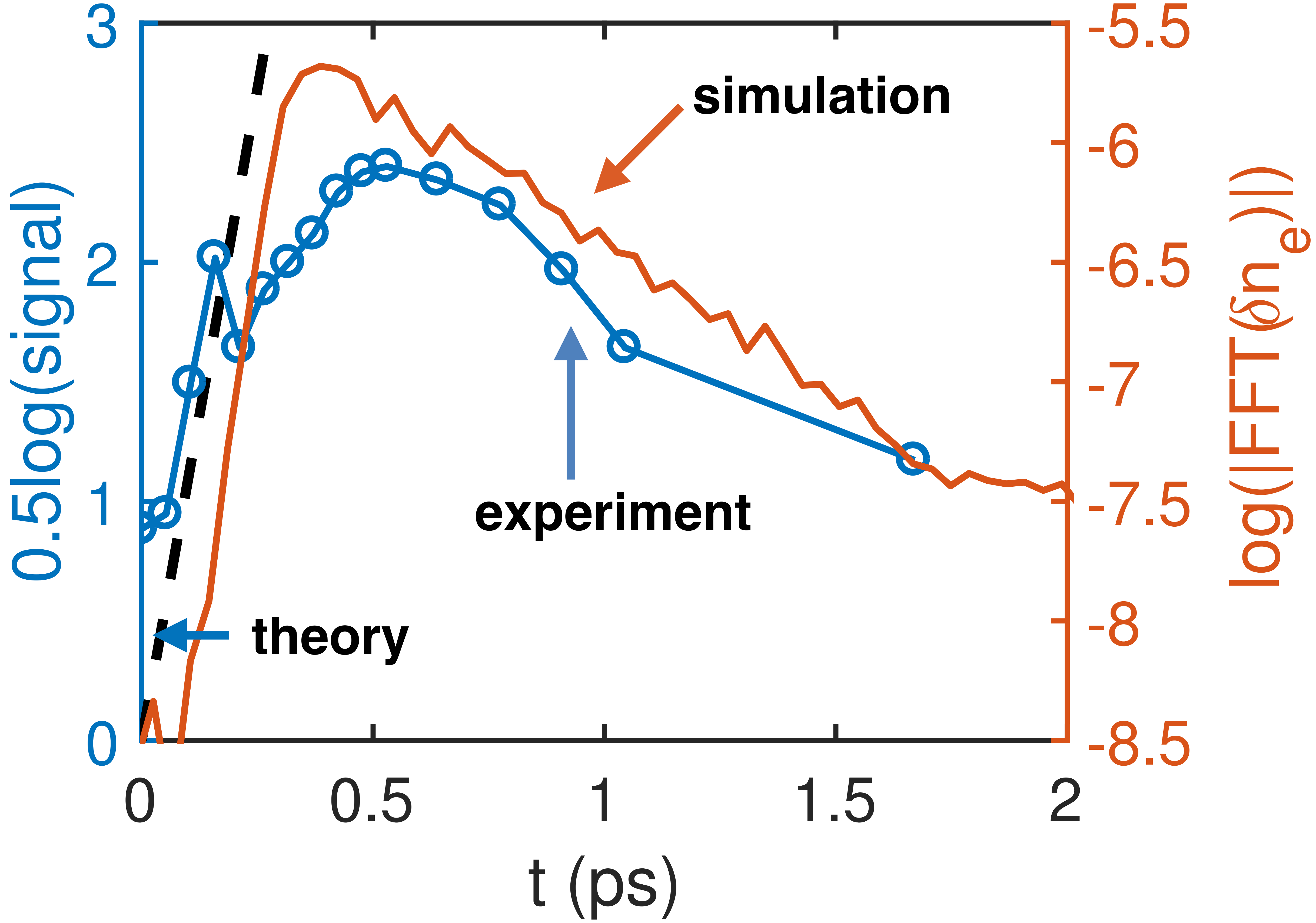
measured TS spectrum as a function of time



magnitude of the electron feature (streaming instability)



- The linear growth and the nonlinear evolution of the streaming instability were measured;
- Experiment, Kinetic theory and PIC simulation agree well with each other;

Filamentation instability

The very similar behavior of the electron feature and the zero-frequency feature within the 1 ps suggests that they may have the same driven source- the counter-propagating streams.

measured TS spectrum as a function of time

Current filamentation instability: proposed experiment at FACET-II

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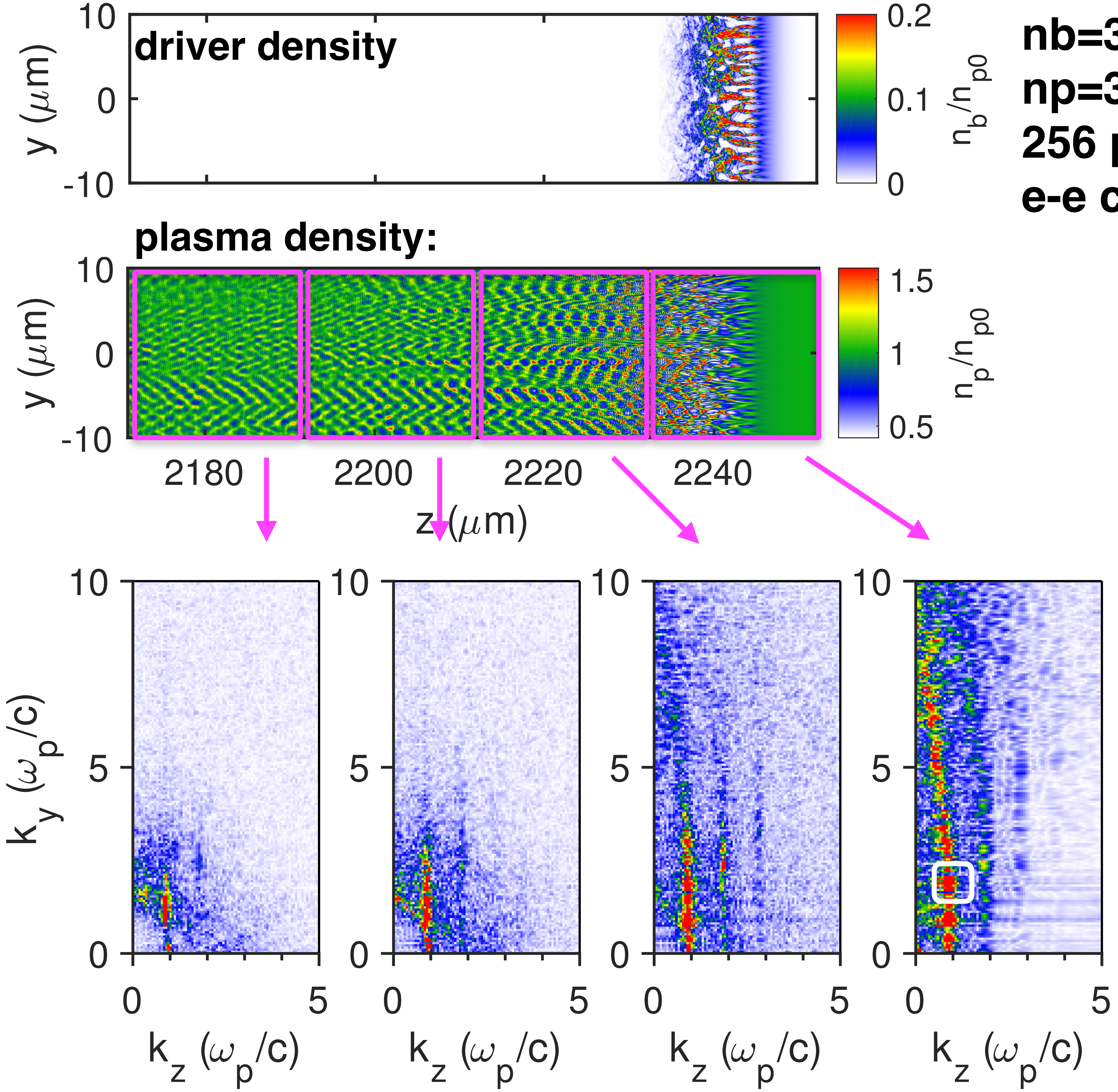
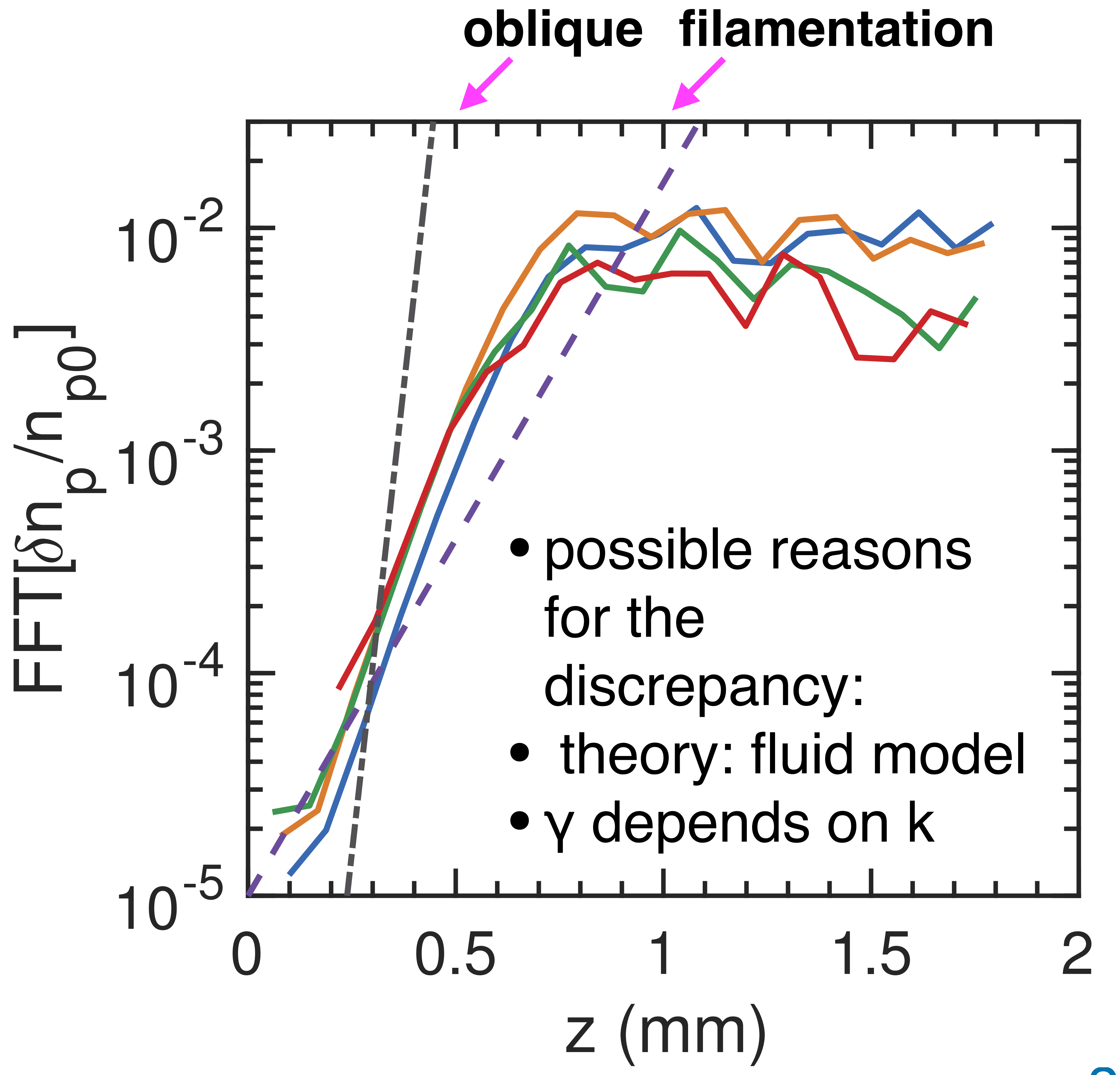


nb=3e19 cm^{-3}, σ_z=2.8 μm
np=3e20 cm^{-3}, 20 eV
256 particles/cell
e-e collisions included

- In collaboration with S. Corde at LOA, F. Fiuza, V. Yakimenko, M. Hogan, etc at SLAC

density fluctuation at kz=kp, ky=2kp:



Summary

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- Theory and PIC simulations show that it is possible to generate high brightness, low emittance e- beams using downramp trapping
  - such injected beams may serve as drivers for beam acc. in crystals and nano-structures
- Using time-resolved Thomson scattering, we have measured instabilities growing in an OFI plasma to test kinetic theory
  - streaming instability
  - filamentation instability
- Beam current filamentation instability may play important roles in acceleration in Crystals/Nano-structures